CRACK ARREST FRACTURE TOUGHNESS MEASUREMENT OF A QUENCHED AND TEMPERED SHIP PLATE STEEL.

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I. A. BURCH AND J. H. UNDERWOOD

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Abstract

A quenched and tempered HSLA type ship plate steel was used to investigate the influence of dynamic effects on crack propagation and arrest behaviour and to measure the static arrest toughness, K_{Ia}. The specimen type used was a wedge-loaded modified compact tension specimen which provides fixed grip conditions during crack extension. Under fixed grip conditions no external work is performed on the specimen after crack initiation and only elastic strain energy stored prior to crack initiation is utilized for crack propagation, usually allowing the propagating crack to arrest within the confines of the specimen.

The tests conducted on this steel gave results that cast doubt on the geometry and crack velocity independence of the static crack arrest fracture toughness parameter. The test results show crack arrest fracture toughness values appear to decrease with increases in kinetic energy input indicating kinetic energy may be utilized during crack extension.

The measured crack arrest fracture toughness values for this steel range from 43 to 60 MPa$\sqrt{m}$ in the longitudinal orientation and 48 to 62 MPa$\sqrt{m}$ in the transverse orientation at - 60°C.

For this series of tests, kinetic energy input was increased by employing side grooves of increasing depth. An increase in side groove depth from a non side grooved specimen to 6% (of specimen thickness) per side decreased the measured K_{Ia} by 5% in both longitudinal and transverse orientations, while an increase in the side groove depth to 12% per side decreased the arrest toughness by 12% (measured in the transverse orientation only).

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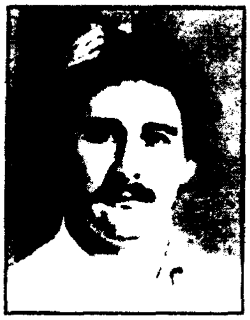

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Crack Arrest Fracture Toughness Measurement of a Quenched and Tempered Ship Plate Steel

1. Introduction

The steel for the pressure hull of the Collins class submarine for the Royal Australian Navy, must meet certain minimum physical property requirements to ensure structural integrity during service. One property of ship steels which describes the dynamic behaviour is the dynamic fracture toughness, K_{ID} although there is as yet no minimum dynamic toughness requirement for the pressure hull steel. If the dynamic toughness is known, an assessment can be made as to how the structure will behave if a propagating crack is present.

Crack propagation occurs as a result of the release of stored elastic strain energy, but during crack extension kinetic energy is produced that may contribute to crack propagation. The dynamic toughness may also be dependent on crack speed for materials which are strain rate sensitive [1].

The complete characterization of crack propagation and arrest behaviour would require a full dynamic analysis of the structure containing the crack. A dynamic analysis would separate contributions attributed to kinetic energy and incorporate strain rate sensitivity allowing the material dynamic fracture toughness, K_{ID}, to be determined. Such an analysis would need to be comprehensive and in itself would be subject to many errors, particularly where assumptions as to loading and structural response have to be made.

An alternative approach is to use the crack arrest fracture toughness, K_{Ia} [1] which is considered to reflect dynamic mechanical properties. This fracture toughness measurement is one which characterizes the ability of the material to arrest rapidly propagating cracks. K_{Ia} is the static value of stress intensity factor following crack arrest [2]. Whilst this method of analysis does not include dynamic effects (the velocity dependence and kinetic energy recovery), measurement of the static crack arrest fracture toughness, K_{Ia}, has produced consistent results where different dynamic effects may have been anticipated [3]. Thus, measurement of the static stress intensity factor following arrest should adequately describe the crack arrest condition.

Due to the consistency of K_{Ia} results reported by Crosley and Ripling [3] and the minimal measurements required to be taken during a test (measurement of the crack opening displacement and the final crack jump length), the K_{Ia} measurement procedure appears attractive for simpler characterization of dynamic fracture properties.

In the present study, an investigation of the static method of analysis was undertaken to confirm that K_{Ia} was a reliable material property for assessing dynamic fracture toughness. The steel used in this investigation was a quenched and tempered, 690 MPa yield stress steel designated BIS 690, this steel being a precursor to the steel finally chosen for the pressure hull of the Collins class submarine. The present work was initiated to enable the measurement of dynamic fracture toughness of steels used for ship and submarine pressure hulls. This report also reviews the principles of dynamic toughness measurement.

2. *Crack Arrest Concepts*

In dynamic fracture mechanics the toughness parameter, K_{ID}, is used to describe the stress state ahead of a propagating crack where K_{ID} may depend on the crack velocity for strain rate sensitive materials. A feature of all K_{ID} versus velocity curves is that a lower limit of dynamic toughness exists, known as K_{Im}, the minimum dynamic fracture toughness (see Fig. 1).

Figure 1 illustrates the types of behaviour associated with strain rate sensitive materials each displaying a minimum dynamic fracture toughness, K_{Im}.

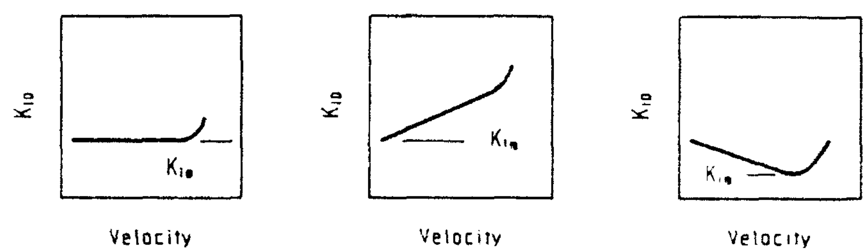


Figure 1: Schematic representation of K_{ID} – velocity curves identifying K_{Im}, the minimum dynamic fracture toughness [1].

When analysing crack propagation and arrest behaviour, there are two possible approaches that can be followed to characterize the propagation/arrest process.

The simplest approach is based on the premise that crack arrest is identical to the reverse of the initiation process [4]. As soon as the propagating crack stress intensity falls below the arrest toughness value, the crack arrests. Kinetic energy interaction and the dynamic fracture toughness/velocity dependence has negligible influence on

arrest toughness. If this view is correct and crack arrest occurs at $K_I = K_{Im}$, then the static arrest toughness, $K_{Ia} = K_{Im}$ and K_{Ia} is a unique material property.

The alternative view considers the inclusion of dynamic effects essential. Mott [5] was first to consider kinetic energy as contributing to crack driving force where kinetic energy is built up in the structure during the initial period of crack extension. For a moving crack, the kinetic energy is associated with the lateral movement of material on either side of the crack and, as the crack propagates, this material moves perpendicular to the crack direction with a velocity proportional to the crack velocity. The material behind the crack tip has mass and velocity and, as a consequence this kinetic energy is available for crack extension.

The unloading of crack surfaces as crack propagation occurs requires continual re-adjustment of the stress field surrounding the crack tip. The speed of this re-adjustment (the crack velocity) is inhibited by the material inertia and the kinetic energy produced is transmitted as stress waves. These stress waves will only interact with the crack tip by reflecting off boundary surfaces. In either case kinetic energy is converted to strain energy which enables it to contribute to crack extension.

For an infinite body, the static stress field surrounding the crack tip after arrest is described by K_{Ia} [6], the static value of stress intensity factor following arrest. The influence of stress waves is not felt at the crack tip as there are no boundary surfaces to reflect the stress waves back to the crack tip.

2.1 *The Static Approach*

Crosley and Ripling [2] have proposed a method of determining static arrest fracture toughness. This method is based on the assumption that kinetic energy produced during crack extension plays no role in crack extension and that there is no velocity dependence on dynamic toughness. Crosley and Ripling postulate that the crack tip loading condition, as expressed by the strain energy release rate, G, adequately describes the arrest condition.

During crack propagation, the strain energy release rate under conditions where kinetic energy is negligible is given by

$$G = dw/da - dU/da \tag{1}$$

where
W = external work performed on the structure
U = strain energy in the system
a = crack length

The strain energy release rate, G_I, together with the fracture energy R_D (dynamic fracture energy consumed by the crack) establish a criterion for crack arrest, occurring when

$$G_I < R_D \tag{2}$$

or, using the stress intensity approach

$$K_I < K_{Ia} \tag{3}$$

2.2 *The Dynamic Approach*

The basic premise of linear elastic fracture mechanics is that crack propagation is possible only when the energy released by a body is at least equal to that absorbed by an extending crack [7]. In the dynamic analysis, all of the energy contributions to crack extension require inclusion to determine the actual material arrest toughness.

A kinetic energy term is added to the energy balance (equation 1) to account for dynamic effects. This can also be expressed in terms of G,

$$G = dW/da - dU/da - dT/da \qquad (4)$$

where W = work performed on the structure by external sources
U = strain energy in the system
T = kinetic energy contribution to crack extension
a = crack length

The contribution of kinetic energy to crack extension has been analysed by Kanninen [8] for a double cantilever beam specimen. Figure 2 illustrates the strain and kinetic energy contributions during crack extension.

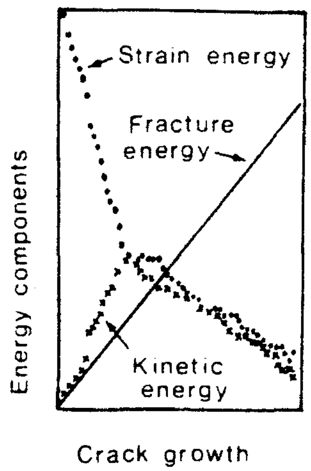


Figure 2: Distribution of energies during crack propagation in a double cantilever beam specimen [8].

During the initial phase of crack extension, fracture is supported solely by the release of strain energy. If no external work is performed on the structure or the specimen as the crack propagates, the strain energy remaining will reduce until it falls below the energy required for fracture. This is the predicted point of arrest if there is no kinetic energy contribution during crack extension.

The analysis by Kanninen [8] shows that the kinetic energy rises to a maximum at the statically determined arrest point and then decreases as crack extension continues. Kinetic energy is utilized for increasing the crack length, this is borne out by the

decrease in kinetic energy in the system as the crack length increases. However not all kinetic energy is recovered during crack propagation and that which remains is converted to strain energy when the crack arrests. A dynamic analysis is necessary to determine the amount of kinetic energy produced and recovered in order to accurately determine the strain energy release rate and therefore the dynamic arrest toughness.

2.3 *Maximum and Minimum Energy Utilization Approximations*

Due to the complexity in performing a dynamic analysis, maximum and minimum energy utilization approximations [9] can be used to determine upper and lower bounds of dynamic toughness. Where no external work is applied during crack propagation and assuming all kinetic energy produced during crack growth is utilized in crack growth, the maximum energy utilization approximation can be used. Hoagland *et al.* [10] has shown that in this situation the dynamic toughness, K_{Im}, can be approximated by

$$K_{Im} = \sqrt{K_{Ia} K_{Q}} \qquad (5)$$

where K_{Ia} = static stress intensity factor following arrest
K_{Im} = minimum dynamic fracture toughness
K_{Q} = initiation toughness (from a blunt notch)

This energy approximation requires the crack jump length to be comparable to the largest dimension of the body/specimen to allow kinetic energy interaction with the crack tip prior to arrest.

If the crack jump length is short and arrest occurs before any kinetic energy interaction with the crack tip the dynamic toughness can be described by

$$K_{Im} = K_{Ia} \qquad (6)$$

Freund [6] has shown that the stress intensity ahead of an arrested crack in an infinite plate can be described by K_{Ia}. When a crack jump event is so brief that the crack arrests before any kinetic energy interaction via the boundary surfaces, then the dynamic toughness can also be described by K_{Ia}.

3. Experimental

3.1 Material

The steel used was a quenched and tempered martensitic steel, designated BIS 690. The chemical composition and mechanical properties are listed in Tables 1 and 2 respectively. The microstructure, consisted of tempered martensite and is shown in Figure 3.

Figure 3: *Microstructure of BIS 690 steel consisting of tempered martensite. X 500*

Table 1: *Chemical composition of BIS 690 ship plate steel (%)*

C	Mn	Si	Ni	Cr	Mo	B	Ti	Nb	V
0.16	1.5	0.4	0.25	0.35	0.4	0.005	0.05	0.05	0.09

Table 2: *Mechanical properties of BIS 690 ship plate steel*

Yield Stress	690 MPa
UTS	780 MPa
Elongation (on 5.65 √ So gauge length)	16%
Charpy impact energy	50 J at - 40°C

3.2 *The Modified Compact Crack Arrest Specimen and K-Calibration*

The ASTM crack arrest test procedure [11] on which the arrest toughness measurements of BIS 690 steel were based, uses a wedge loading arrangement shown schematically in Figure 4. The modified compact type specimen used for this test is shown in Figure 5.

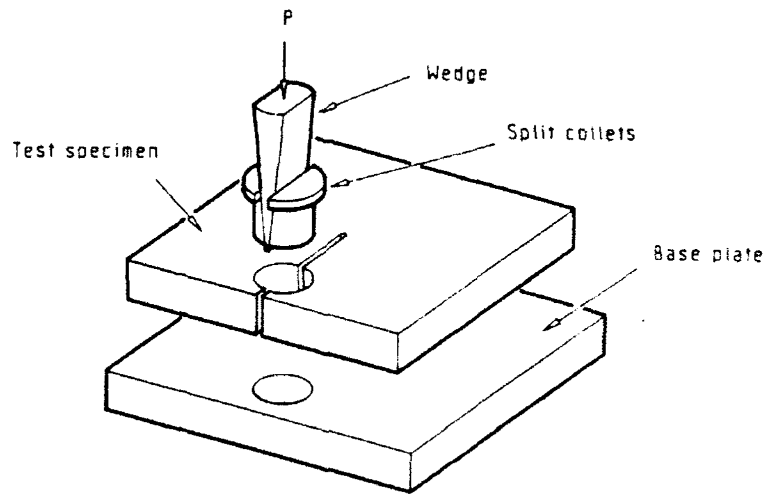


Figure 4: Arrangement for wedge loading of the modified compact tension specimen.

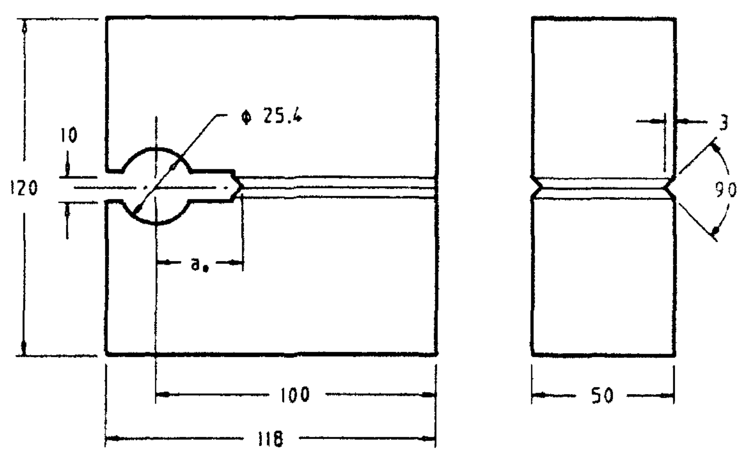


Figure 5: K_{Ia} *specimen and dimensions.*

The wedge loading arrangement is employed because it reduces specimen/machine interaction during the crack propagation event by increasing the effective machine stiffness thus approaching fixed displacement test conditions. If any significant interaction occurred, it would add extra crack driving force to the specimen, increasing the arrested crack length which would result in an underestimation of the arrest toughness.

The wedge loading arrangement allows the crack to propagate into a diminishing strain energy field. When the crack extends, no external work or energy input is performed on the specimen and the stored elastic strain energy decreases with increasing crack length. At some point within the confines of the specimen the remaining elastic strain energy will fall below the energy requirement for continued crack propagation and as a result, the crack arrests.

The K calibration employed for the ASTM test procedure [11] is from experimental compliance results of Crosley and Ripling [12] given by equation 7:

$$K = Y(1 - a/W)^{1/2}\, \delta E\, (B/B_N)^{1/2} / W^{1/2} \tag{7}$$

where
- a = crack length
- W = specimen width
- δ = crack opening displacement
- E = Young's Modulus
- B = Specimen width
- B_N = Not specimen thickness at side grooves

$$Y = 2.24\,(1.72 + 0.9(a/W) + (a/W)^2) / (9.85 - 0.179(a/W) + 11\,(a/W)^2)$$

for the range $0.35 < a/W < 0.85$.

Underwood and Newman [13] have compared these experimental compliance results for a compact crack arrest specimen with Newman's collocation results for a compact tension specimen [14]. The comparison shows the collocation results to be more accurate at larger a/W values than the experimental compliance results. As the crack length following a run/arrest segment generally falls into the range of $a/W > 0.7$, the collocation results appear to be more suitable for crack arrest testing.

The K calibration of equation 8 represents curve fitting to Newman's collocation data and the known deep crack limit.

$$K = Y(1 - a/W)^{1/2}\, \delta E\, (B/B_N)^{1/2} / W^{1/2} \tag{8}$$

where

$$Y = 0.748 - 2.76(a/W) + 3.56(a/W)^2 - 2.55(a/W)^3 - 0.62(a/W)^4$$

for the range $0.2 < a/W < 1.0$.

The thickness for maintaining plane strain conditions for a propagating crack compared to a stationary crack is substantially reduced due to the dependence on the $(K_{ID} / \sigma_{yD})^2$ ratio, where K_{ID} is the dynamic fracture toughness and σ_{yD}, the dynamic yield strength. Plane strain conditions are maintained for a stationary crack if the specimen thickness

$$B > 2.5 \; (K_{IC} / \sigma_y)^2 \qquad (9)$$

Hoagland *et al.* [1] suggest the thickness, inferred from measurements, to maintain plane strain conditions for a propagating crack in A533B steel is

$$B > 0.3 \; (K_{Im} / \sigma_y)^2 \qquad (10)$$

or

$$B > 0.3 \; (K_{Ia} / \sigma_y)^2 \qquad (11)$$

The material BIS 690 is supplied in 50 mm thick plate with a minimum static yield stress of 690 MPa. To maintain plane strain conditions, and using the above relationship the maximum crack arrest fracture toughness for the material at ambient temperature is found to be:

$$(0.05 / 0.3)^{1/2} \times 690 = 280 \; \mathrm{MPa}\sqrt{\mathrm{m}}$$

3.3 *Crack Initiation*

Initiation of the crack is facilitated by depositing a brittle weld bead (Fig. 6) at the base of the starter notch and then re-machining a 90° included angle notch to act as a stress concentration.

The main purpose of the weld bead is to reduce the initiation toughness, which reduces the elastic strain energy in the specimen, and therefore any subsequent kinetic energy effects once a crack has propagated. It also helps prevent plastic deformation at the notch tip prior to crack propagation.

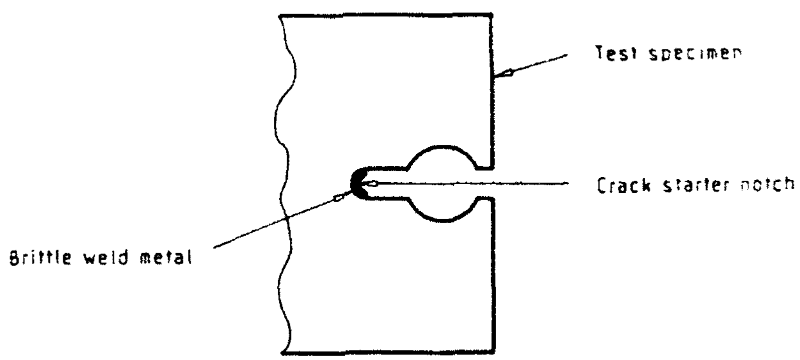


Figure 6: Crack starter notch.

The use of brittle weld beads as crack initiators produces a problem in calculating maximum energy utilization approximation values of arrest toughness. The initiation toughness obtained during a test may not be the initiation toughness of the parent plate but that of the weld bead and minimum energy utilization approximations may have to suffice for measurements of dynamic fracture toughness. Dynamic fracture toughness values lie between the maximum and minimum energy utilization approximations, depending on the amount of kinetic energy consumed during crack extension.

3.4 *Effects of Side Grooves*

To investigate the effects of kinetic energy input during crack extension on K_{Ia} values, side grooves of varying depths were machined into specimen side faces; Hoagland [1] observed that an increasing side groove depth increased the initiation toughness (from a blunt notch). Increasing the initiation toughness increases the crack velocity following initiation. Since kinetic energy is dependent on crack velocity, by varying the crack velocity it is possible to observe the effect of an increasing amount of kinetic energy on arrest toughness values.

3.5 *Test Program*

Crack arrest behaviour of BIS 690 was assessed in the longitudinal and transverse orientation on specimens without side grooves and with side grooves. Side grooves of (a) 12% (3 mm per side) of total thickness and (b) 24% (6 mm per side) of total thickness were used, profiles of these side grooves are illustrated in Figure 7. All combinations of orientation and side groove depth were carried out at - 60°C.

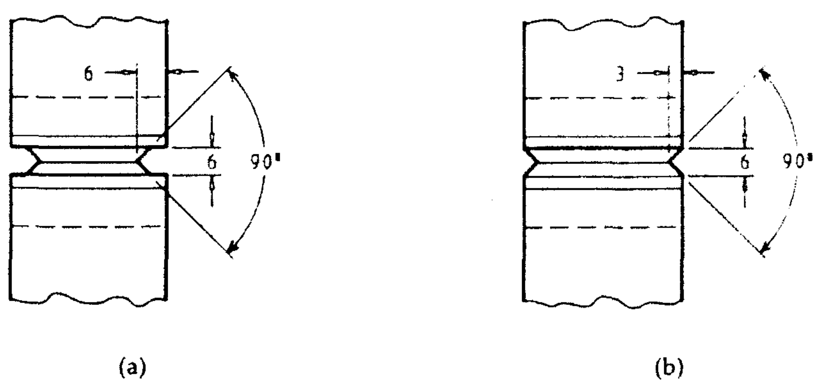


Figure 7: (a) 6 mm per side grooves and (b) 3 mm per side grooves.

Crack initiation toughness or K_{IC} tests were also performed in the longitudinal and transverse orientations, but without side grooves. The tests were performed at - 60°C. The specimens used in this procedure differed slightly from the standard modified compact specimen, as they contained pin holes in the wedge load line to facilitate fatigue precracking. The presence of pin holes has an effect on the K calibration of compact crack arrest specimens used for initiation toughness measurement. Underwood *et al.* [15], compared the K calibration of the standard ASTM compact specimen [16] with the K calibration of the ASTM compact specimen without pin holes [14]. The two calibrations agree within 1% for $a/W > 0.4$, allowing the arrest toughness K calibration to be used to measure initiation toughness of specimens with pin holes.

Measurement of the arrested crack lengths on K_{Ia} specimens are determined by heat tinting the cracked specimens in an electric furnace at 400°C to promote an oxide coating on the exposed (fractured) surfaces. The specimens were re-loaded to complete the fracture of the specimen and so enable lengths of arrested cracks to be measured.

The crack opening displacement for both K_{Ia} and K_{IC} specimens was measured using a clip gauge, of the type described in ASTM E399-81 [15], attached to the specimen via knife edges. The K calibration requires the knife edges to be a distance W/4 from the load line and this was accomplished using spacer blocks (Fig. 8). The spacer blocks have a two-fold purpose; as well as positioning the knife edges the correct distance from the load line they also serve to retain the clip gauge in position in the event of sudden specimen unloading. When the crack initiates, the specimen arms move outward at a rapid rate followed by a sudden halt which may ordinarily dislodge the clip gauge, making any clip gauge measurements at arrest impossible. The spacers remove this problem by reducing the free distance the clip gauge arms are permitted to move when in position.

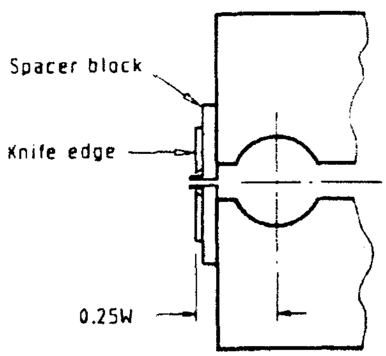


Figure 8: Attachment of knife edges to specimen.

4. Results and Discussion

The results of tests using the ASTM procedure for crack arrest fracture toughness measurement [11] appeared, at least initially, to give consistent results as shown in Table 3 allowing for variability in material behavior due to the small sample size used. The average value for K_{Ia} in the longitudinal orientation (T - L) using the Underwood and Newman calibration was 56 MPa $\sqrt{m}$, and 55 MPa $\sqrt{m}$ for the transverse orientation (L - T). Average initiation fracture toughness values of 128 MPa $\sqrt{m}$ and 148 MPa $\sqrt{m}$ (using the Underwood and Newman calibration) were obtained for the longitudinal and transverse orientations respectively, using the wedge loading technique. The initiation fracture toughness measurements (Table 4) did not produce valid K_{IC} values because the specimens did not conform to the minimum thickness requirement necessary to assure plane strain conditions [16].

Table 3: *Results of K_{Ia} tests at - 60°C*

ID	Orient.	Side Groove Depth (mm)	a_0 / W	K_Q (MPa$\sqrt{m}$) (Underwood & Newman)	K_Q (MPa$\sqrt{m}$) (Crosley & Ripling)	a_f / W	K_{Ia} (MPa$\sqrt{m}$) (Underwood & Newman)	K_{Ia} (MPa$\sqrt{m}$) (Crosley & Ripling)
19	T-L	-	0.18	93	71	0.42	[illegible]	[illegible]
17	T-L	-	0.19	99	77	0.45	57	57
18	L-T	-	0.18	86	65	0.47	49	49
7	L-T	-	0.16	112	52	0.41	62	62
9	T-L	3.0	0.18	151	115	0.65	60	58
8	T-L	3.0	0.175	143	108	0.79	43	41
3	T-L	3.0	0.31	116	107	0.76	56	53
14	L-T	3.0	0.35	112	107	0.80	49	46
16	L-T	3.0	0.32	94	87	0.64	54	53
6	L-T	6.0	0.30	116	106	0.78	48	45
1	L-T	6.0	0.305	170	155			
2	L-T	6.0	0.38	168	164			
4	T-L	6.0	0.32	165	153			

Table 4: *Initiation fracture toughness values from wedge loaded fracture toughness tests of - 60°C*

Specimen Number	Orientation	Fracture Toughness (MPa$\sqrt{m}$) (Underwood and Newman	Fracture Toughness (MPa$\sqrt{m}$) (Crosley and Ripling)
1	T-L	146	147
2	T-L	110	111
3	L-T	141	142
4	L-T	155	156

Although the K_{Ia} values appeared consistent, a further analysis of the test results was made to determine if any variation in K_{Ia} resulted from changes in specimen geometry. Altering specimen geometry by increasing the side groove depth resulted

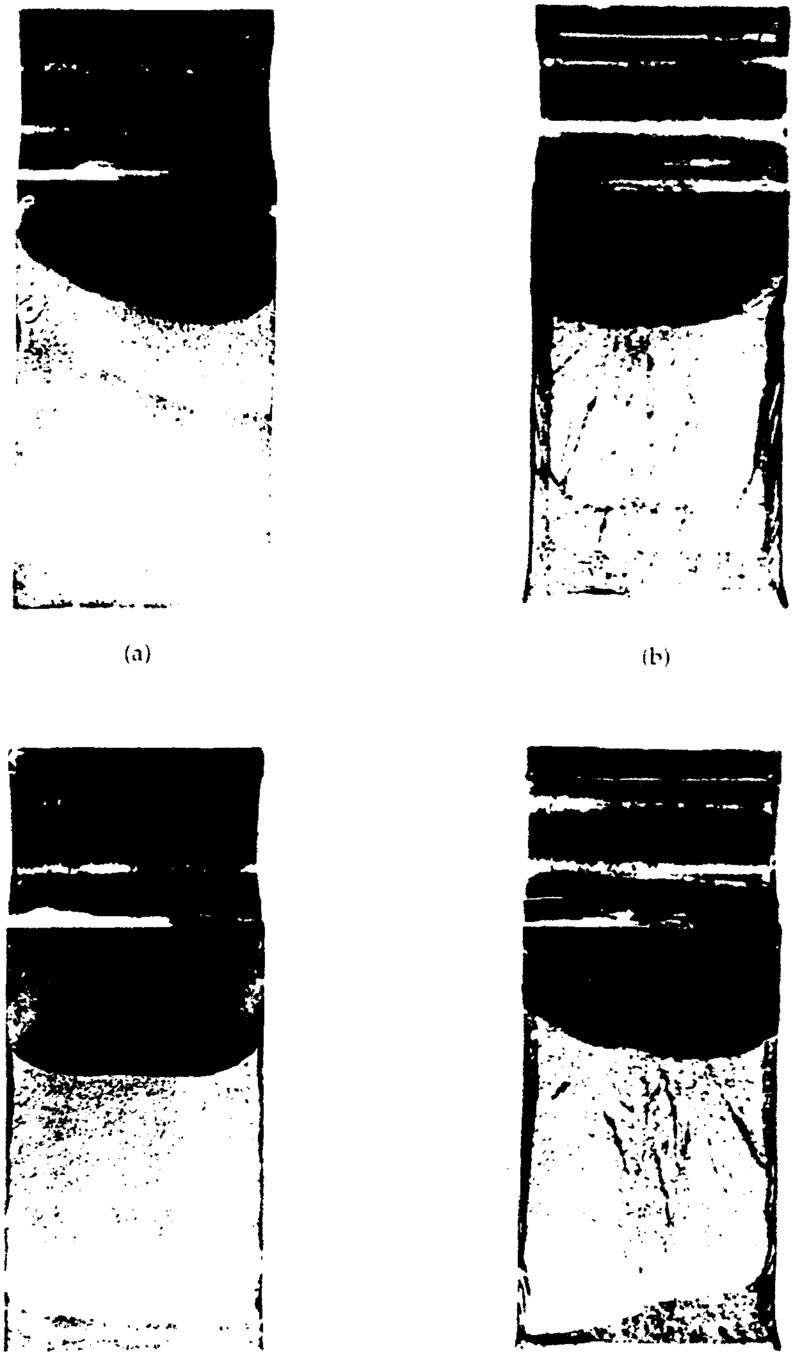
in an increase in initiation toughness, K_Q, and a corresponding decrease in K_{Ia}. The increase in side groove depth to 6% of specimen thickness per side produced a 5% reduction in the average value of K_{Ia} in the longitudinal orientation and 5% in the transverse orientation (Table 3). The group of specimens with 12% side groove depth per side produced only one run/arrest segment of crack extension and the crack arrest toughness value was 8% lower than the shallow side grooved specimens and 12% lower than the non-grooved specimens (Table 3).

While the test program used only a small number of specimens, the observed decrease in K_{Ia} is consistent with an increase in kinetic energy or dynamic input during crack extension. As K_Q increases, crack velocity also increases resulting in greater kinetic energy being available for crack growth. If this kinetic energy is utilized during crack extension, the implication is that the material under test has a lower dynamic toughness as indicated by the K_{Ia} value rather than the K_{ID} dynamic toughness value which includes dynamic (kinetic) contributions. It is possible that the reduction in K_{Ia} with increasing K_Q may be due to material variability or inhomogeneity, but the self consistency of the data suggests that the above explanation is more likely.

Examination of the fracture surfaces in Figures 12, 13 and 14 show that the arrested crack fronts, denoted by the oxidized section of the fracture face, did not always exhibit straight crack jumps. The photographs show some crack fronts run diagonally, an effect possibly due to misalignment of the loading system.

In plane strain fracture toughness testing, slant crack fronts are considered non ideal and are a cause for rejection of data [16]. However, examples are given [17] which show that K_{Ia} data for slant fractures up to 45° agree well with straight crack front K_{Ia} data. Comparison of BIS 690 specimens with straight crack fronts and specimens with slant crack fronts show increases by as much as 26% in arrest fracture toughness, K_{Ia}, when the crack front profile was slanted. This result does not agree with the findings in the literature [17] and may be cause for rejection of data that at present is considered valid. Specimens 7 and 18 have no side grooves and are of the same orientation, but specimen 7 has a slant crack front and a K_{Ia} of 62 MPa $\sqrt{m}$ and specimen 18, a straight crack front and K_{Ia} of 49 MPa $\sqrt{m}$. The shallow side groove data (6% per side) in the longitudinal orientation shows specimen 9 which has a slant crack front, have a K_{Ia} value of 60 MPa $\sqrt{m}$ while specimens 3 and 8, which exhibit reasonably straight crack fronts, have K_{Ia} values of 56 and 43 MPa $\sqrt{m}$ respectively. For the same side groove depth but in the transverse orientation, specimen 16 has a slanted crack front and a K_{Ia} of 54 MPa $\sqrt{m}$ and specimen 14 which had a straight crack front, a K_{Ia} of 49 MPa $\sqrt{m}$.

The wedge loaded initiation toughness values given in Table 4 should not be considered valid, when these values were subject to the thickness criteria of ASTM E399 [16], the specimens did not have the necessary minimum thickness to maintain plane strain conditions. The - 60°C yield strength based on measurements on a similar steel [18] suggest a value of 8% above the 20°C yield strength, this yield strength value and the specimen thickness of 50 mm require the initiation toughness to be less than 107 MPa $\sqrt{m}$ to be valid. Figure 14 shows fracture faces of initiation toughness specimens demonstrating flat fracture, even though they are invalid due to excessive plasticity.



(a) (b) (c) (d)

Figure 12: K_{Ia} *fracture surfaces; no side grooves. (a) Specimen number 7, (b) 17, (c) 18 and (d) 19.*

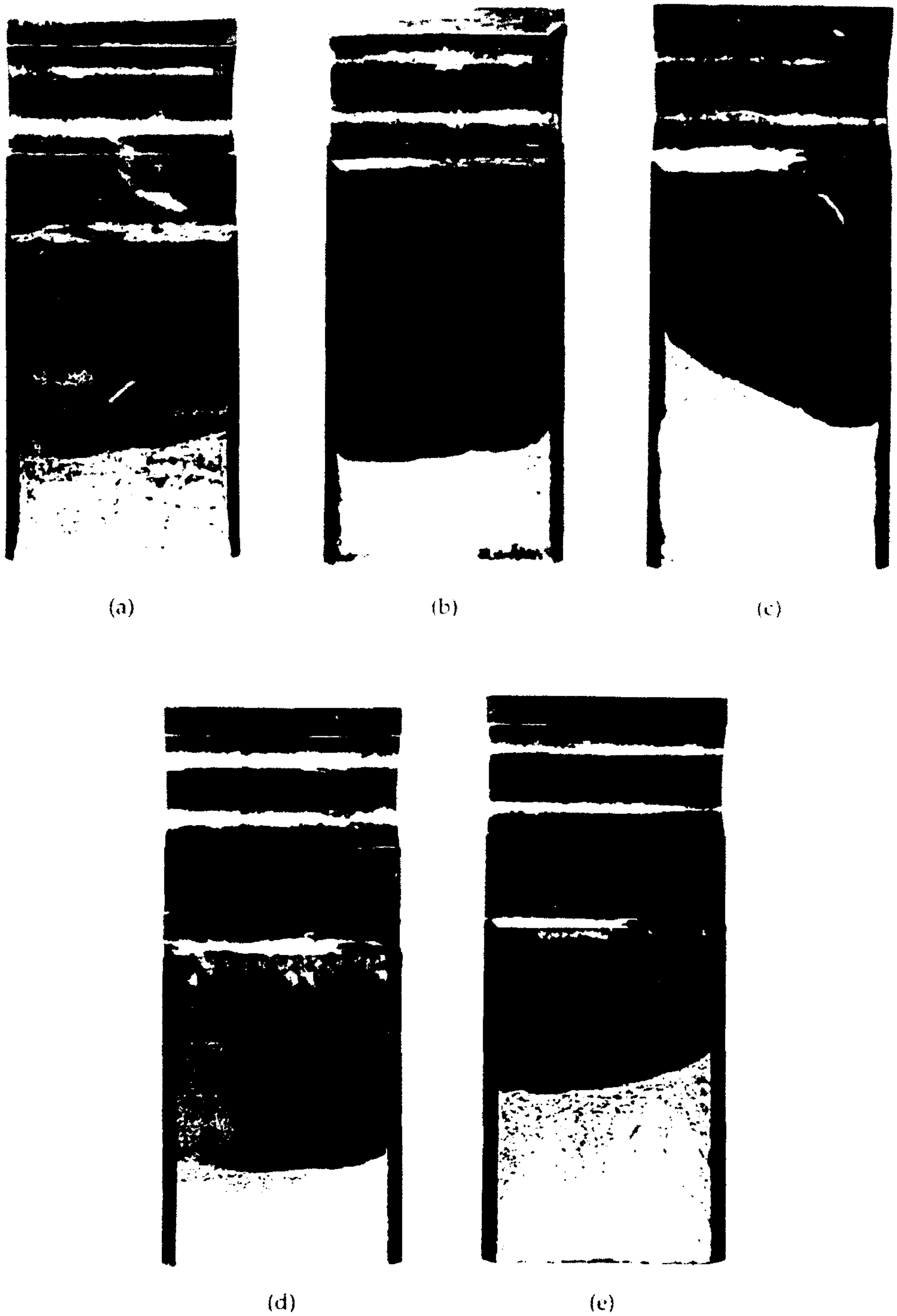


Figure 13: K_{Ia} fracture surfaces; 6% side grooves per side. (a) Specimen number 3, (b) 8, (c) 9, (d) 14 and (e) 16.

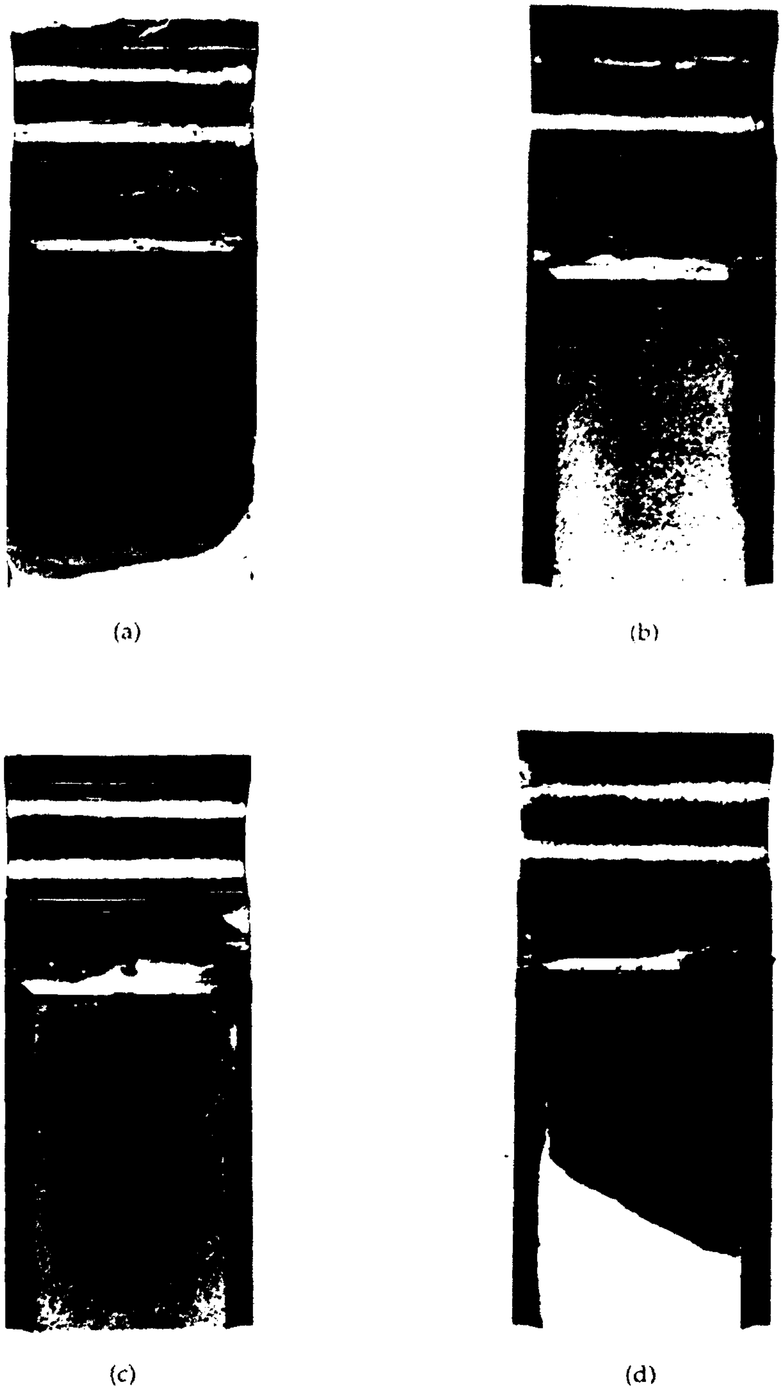
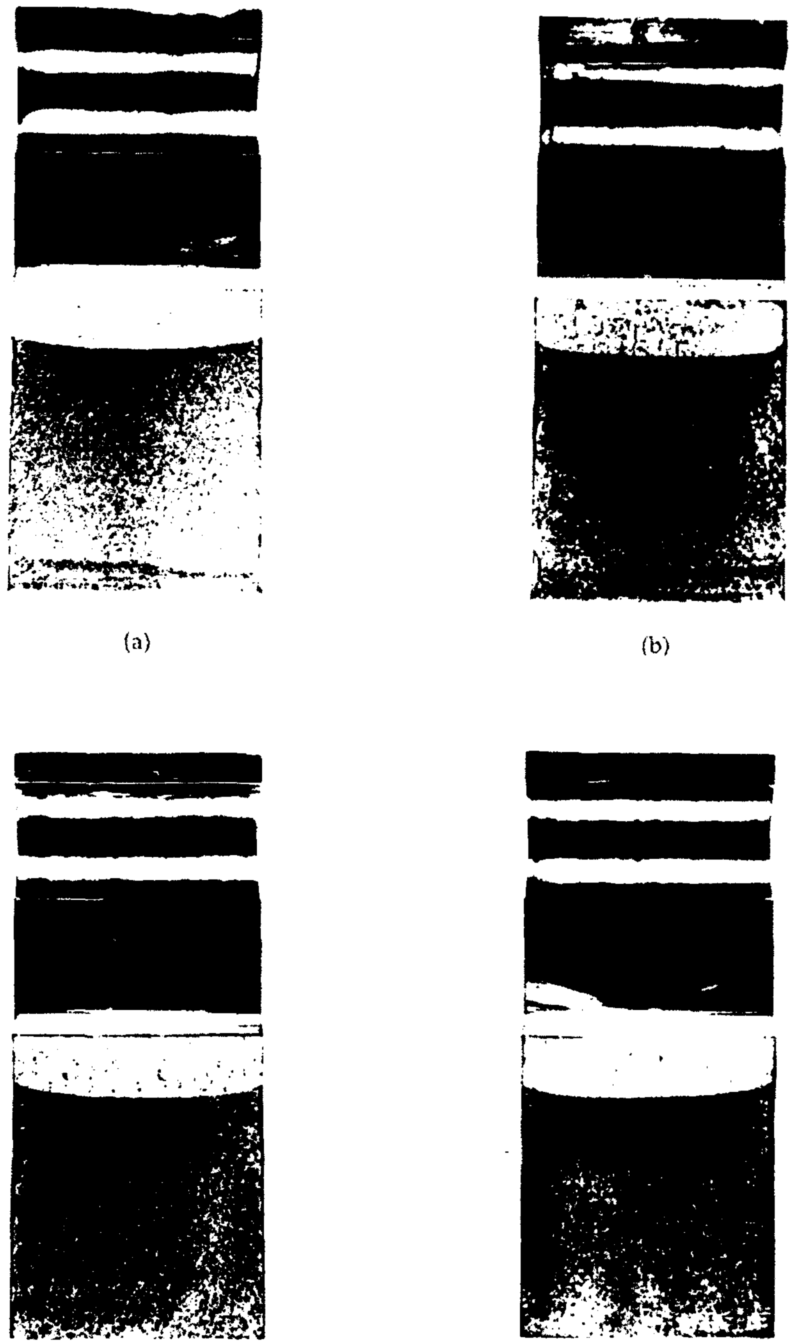


Figure 14: K_{Ia} *fracture surfaces; 12% side grooves per side. (a) Specimen number 1, (b) 2, (c) 4 and (d) 6.*



(a) (b)

(c) (d)

Figure 15: *Initiation toughness fracture surfaces. (a) Specimen number 1, (b) 2, (c) 3 and (d) 4.*

The initiation toughness values were much higher than the arrest toughness values, indicating the crack will propagate more easily once initiated because to facilitate an arrest, the stress intensity factor at the crack tip must fall below the arrest toughness value and not the initiation toughness value. This phenomenon may be due to the increased strain rate associated with dynamic fracture. An increase in strain rate increases the yield strength, delaying the onset of plasticity at the crack tip. Crack resistance is dependent on plastic deformation and, by delaying the onset of plastic deformation, the amount of energy required for continued crack propagation is reduced.

5. Conclusions

For BIS 690 steel, the ASTM test procedure [11] for arrest toughness measurement gave average values of 55 MPa √m and 52 MPa √m for the longitudinal and transverse orientations respectively.

The initiation toughness values obtained using the wedge loading procedure gave average values of 148 MPa √m and 128 MPa √m for longitudinal and transverse orientations respectively. The specimens used for these tests were of insufficient thickness to give valid K_{Ic} values.

Results indicate that dynamic effects may contribute to crack extension. There is a trend of decreasing K_{Ia} values obtained with increasing K_Q values.

Slanted crack fronts appear to affect K_{Ia} values by over-estimating the arrest toughness value.

Arrest toughness K_{Ia} is significantly lower than the initiation toughness indicating that an increased strain rate affects the stress intensity at which cracks propagate in this material.

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Crack arrest fracture toughness measurements of a quenched and tempered ship plate steel

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ABSTRACT

A quenched and tempered HSLA type ship plate steel was used to investigate the influence of dynamic effects on crack propagation and arrest behaviour and to measure the static arrest toughness, K_{Ia}. The specimen type used was a wedge-loaded modified compact tension specimen which provides fixed grip conditions during crack extension. Under fixed grip conditions no external work is performed on the specimen after crack initiation and only elastic strain energy stored prior to crack initiation is utilized for crack propagation, usually allowing the propagating crack to arrest within the confines of the specimen.

The tests conducted on this steel gave results that cast doubt on the geometry and crack velocity independence of the static crack arrest fracture toughness parameter. The test results show crack arrest fracture toughness values appear to decrease with increases in kinetic energy input indicating kinetic energy may be utilized during crack extension.

The measured crack arrest fracture toughness values for this steel range from 43 to 60 MPa $\sqrt{m}$ in the longitudinal orientation and 48 to 62 MPa $\sqrt{m}$ in the transverse orientation at - 60°C.

For this series of tests, kinetic energy input was increased by employing side grooves of increasing depth. An increase in side groove depth from a non side grooved specimen to 6% (of specimen thickness) per side decreased the measured K_{Ia} by 5% in both longitudinal and transverse orientations, while an increase in the side groove depth to 12% per side decreased the arrest toughness by 12% (measured in the transverse orientation only).

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